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DESIGN AND TESTING OF HIGH PERFORMANCE BRUSHES.(U)
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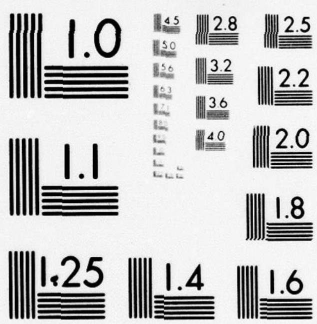

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Yearly Report
Contract N00014-76-C-1009

DESIGN AND TESTING OF HIGH PERFORMANCE BRUSHES

Submitted to:

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Submitted by:

Doris Kuhlmann-Wilsdorf
University Professor of Applied Science

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Yearly Report to Contract N00014-76-C-1009

DESIGN AND TESTING OF HIGH PERFORMANCE BRUSHES

Much progress has been made in the past contract period. This concerned investigations on graphite-silver brushes (Stackpole, SG-142), design and modifications of auxiliary apparatus for the manufacture and testing of metal fiber brushes, and experimental as well as theoretical investigations of the properties of fiber brushes.

The results of these various endeavors have been recorded in three publications of which copies are appended and which in fact constitute the body of the present Yearly Report. This introduction is therefore meant only to summarize the major findings:

With regard to the behavior of silver-graphite brushes conclusive evidence for the formation and destruction of surface films was obtained which are apparently superimposed on the permanently present very thin surface films to be found on all metals. The nature of the latter is presumably much the same as for clean copper and silver surfaces since the film resistivity of this component of the surface film is much the same as that given by Holm for the film on the clean metals. The other component which is prone to build-up and destruction is apparently absent on the cathodic brush. It is concluded that it is mainly composed of lubricating material. This film has a thickness which is increased by moderate heating, and thus initially thickens with rising current and brush velocity. However, at some not-well-defined level of applied voltage, it is destroyed, in which process mechanical action aids, so that the film disruption occurs at a lower level of heating if the speed is increased. Most remarkably, the coefficient of friction is not much different whether the discussed film is present or not. Correspondingly, it is tentatively concluded that the performance of the SG-142 will be best at high current densities.

Metal fiber brushes with different combinations of fiber and matrix materials have been made by a method of successive drawing, bundling and redrawing, much as in the production of multi-filamentary materials as are widely used for superconducting magnets, followed by etching away the matrix material to the desired depth to expose the fibers.

Measurements of the brush resistance of such brushes show no difference between anodic and cathodic brush. In the light of the results pertaining to surface films on silver-graphite brushes this may not be surprising since the brushes are run without deliberate lubrication. At low brush pressures the brush resistance rises with velocity, the more so the thinner the fibers. This is considered to be due to aerodynamic lift. The effect vanishes if the brush pressure is increased. At a brush pressure of about 1 lb/in^2 (several thousand N/m^2) the brush resistance is independent of velocity up to at least 35 m/sec, with preliminary indications that it is still substantially the same at 50 m/sec. Similarly, the brush resistance is independent of current density up to 650 A/cm^2 (about 4200 A/in^2) of geometrical brush area.

The best results were obtained with gold fiber brushes with fiber diameters about 20 microns and packing density between 10% and about 15.5%. When these were run on a carbon-gold surface that was applied by the AMP Corporation using a proprietary process, the electrical loss at 650 A/cm^2 lay at about 0.1 Watt per brush per ampere conducted independent of velocity, certainly up to 35 m/sec and probably up to at least 50 m/sec. The limitations on current density as well as velocity in these tests were imposed by the testing equipment and do not reflect the limit of brush performance.

Theoretical analysis revealed that the number of a-spots per fiber is near unity for the brushes while running, and is three in the stationary case. This is believed to be due to the inability of the fiber tips to reorient fast enough to follow the rapid contour changes of the opposing surface when there is relative motion between the brush and its substrate. For the remainder, the results indicate that the brush resistance is essentially controlled by film resistance, and that the contact spots

behave elastically. The film resistivity inferred from the data in relation to the theory is $\sigma_F = 5\times10^{-13}\Omega m^2$. This is close to the smallest film resistivity quoted by Holm in his book for clean gold surfaces.

The dependence of brush resistance on load in the stationary case is well described by the theory; and also the relative magnitudes of the brush resistances for brushes of different construction obey the theory. Thus, it is considered that the behavior of the brushes is well understood. The perhaps most remarkable feature of the results is that the contribution of tunnelling electrons in an annular area about the individual a-spots makes a very significant contribution to the conductivity. This is due to the fact that the individual a-spots are very small indeed, and are very small compared to the radius of curvature of the contacting surfaces.

Publications under the Contract follow.

Electrical Contacts - 1979
Ill. Inst. Techn., Chicago, IL

EFFECTS OF SURFACE FILMS ON THE PERFORMANCE OF SILVER GRAPHITE (75 w/o Ag, 25 w/o C) ELECTRIC BRUSHES

BY

S. Dillich and D. Kuhlmann-Wilsdorf
Department of Materials Science
University of Virginia
Charlottesville, Virginia 22901

ABSTRACT

The brush resistance of silver graphite (Stackpole SG142, 75 w/o Ag, 25 w/o C) has been investigated over a range of speeds up to 35 m/sec and a range of current densities up to 46.5 x 10^5 $\frac{A}{m^2}$. The data show conclusive evidence for the build-up and breakdown of surface films due to the graphite lubrication, and also for a persistent surface film of about 10^{-12} ohm-m^2 film resistivity. Film breakdown appears to be triggered at some critical combination of current density and speed. In the absence of the lubricating film, the brushes run at much lower electrical loss and with a reduced coefficient of friction. This result suggests that the optimum performance of the brush is at high speeds and current densities.

INTRODUCTION

The transfer of current between solids can be achieved in two basic ways; with or without the presence of deliberate lubrication at the contact interface The obvious advantage of adjuvant lubrication in limiting the frictional losses of electrical brushes is offset by a corresponding high film resistance at the electrical contacts. If no lubrication were used in conjunction with monolithic solid brushes, the very low brush load necessary to avoid high frictional losses would contribute enlarged constriction effects to their resistive behavior, or so it is generally believed.

Silver graphite composite brushes have already been studied extensively by researchers at the Westinghouse Research and Development Center.[1,2,3] Somewhat at variance with our findings, they concluded that the film contribution to the total resistance is negligible for brushes with high metal content.[4] Since these brushes are the best commercially available for high current density applications, a detailed investigation of the film behavior is necessary in order to determine as conclusively as possible to what extent lubrication at electrical contacts is advantageous.

As will be seen, the results of the present study indicate the possibility of eliminating lubricating films, thereby decreasing the contact resistance without raising the coefficient of friction.

EXPERIMENTAL PROCEDURE AND RESULTS

The Stackpole SG 142 brushes (75 w/o Ag, 25 w/o, C) were tested on an apparatus described in an earlier paper.[5] Cooling has been added by blowing test atmosphere gas over the brushes. This method is effective in reducing and stabilizing the brush bulk temperature. However, it has not been determined by how much the contact interface temperature is reduced.

The major testing conditions are summarized in Table 1. At fixed sliding speed and brush load, successively higher currents were passed through the brushes after which the current was stepwise reduced through the same sequence of values. Unless otherwise noted, the time between measurements at successive current densities was on the order of one minute.

The test results have been assembled in Figures 1-5 and Tables 2-4. Although data have been collected over a fairly extensive range of test parameters, the number of experimental variables is too high to allow for exhaustive study. Therefore, the brush tests discussed in this paper were made at a fixed brush load with sliding speeds between 5.1 m/sec and 35 m/sec and current densities between 2.3 x 10^5 $\frac{amps}{m^2}$ and 46.5 x 10^5 $\frac{amps}{m^2}$.

For the sake of brevity, this paper concentrates on the anode brush test results. The cathode brush generally

TABLE 1 Test Conditions

Brushes:	Stackpole Silver Graphite Composite Brushes, SG 142 (75 w/o Ag, 25 w/o C)
Brush Face Area:	0.67 in^2 = 0.43 cm^2
Brush Angle:	15^o trailing
Number of Brushes:	two brushes, one positive, one negative, run on separate tracks
Brush Force:	8.3 Newtons
Rotor:	Copper 8.13 x 10^{-2} m diameter (3.2 in. diameter)
Sliding Speeds:	5.1 m/sec, 13 m/sec, 26 m/sec, 30 m/sec, 35 m/sec
Currents:	10A, 34A, 67A, 100A, 134A, 167A, 201A
Atmosphere:	ambient air when noted otherwise: humidified CO_2, 22^o D.P.

exhibited a lower voltage drop than the anode brush, otherwise its contact behavior was similar to that of the anode brush.

DISCUSSION

Contact Resistance

The total resistance per brush, R_T, calculated from measured values of voltage drop and current is composed of three terms: the constriction resistance, R_C, the bulk resistance of the brush, R_B, and the film resistance at the brush rotor interface, R_F, so that

$$R_T = R_C + R_B + R_F, \qquad (1)$$

The expressions for the constriction resistance and the film resistance are[6]

$$R_C = \frac{0.4\ (\rho_B + \rho_R)}{(nA_T)^{1/2}} \qquad (2)$$

and

$$R_F = \frac{\sigma_F}{A_T} \qquad (3)$$

where ρ_B and ρ_R are the resistivities of the brush and rotor respectively, n is the number of contact spots, σ_F is the film resistivity, and A_T is the true area of mechanical contact. In the case of fully plastic behavior of the a-spots, A_T is given by[7]

$$(4) \quad A_T = \frac{P}{\xi H} \qquad (4)$$

where P is the applied normal force on the brushes, H the brush indentation hardness, and ξ a constant approximately equal to 1/3.

In evaluating the constriction resistance values of H, and of brush electrical conductivity, σ_e, determined by I. R. McNab and J. L. Johnson[8] for the

TABLE 2

Fig. #	v m/s	J A/cm^2	V_{drop} V	R_T mΩ	R_F mΩ	σ_F x10^9 Ωm^2
1	5.1	232.5	0.078	0.78	0.49	4.0
	5.1	310.0	0.098	0.74	0.45	3.8
	5.1	387.0	0.105	0.63	0.34	2.8
	5.1	465.0	0.115	0.57	0.28	2.3
1	26	232.5	0.202	2.60	2.31	19.2
	26	310.0	0.356	2.68	2.39	20.0
	26	387.5	0.265	1.59	1.30	1.1
	26	465.0	0.100	0.50	0.21	1.8
1	30	232.5	0.234	2.34	2.05	17.1
	30	310.0	0.280	2.11	1.85	15.0
	30	387.5	0.345	2.07	1.78	15.0
	30	465.0	0.210	1.04	0.75	6.3
1	35	232.5	0.195	1.95	1.66	14.0
	35	465.0	0.140	0.70	0.41	3.4
3	13	387.5	0.140	0.84	0.55	4.6
	13	465.0	0.252	1.25	0.96	8.0
4	13	310.0	0.145	1.09	0.80	6.7
	13	387.0	0.170	1.02	0.73	6.1
	13	465.0	0.180	0.90	0.61	5.1
4 air	13	310.0	0.120	0.90	0.61	5.1
	13	387.5	0.140	0.84	0.55	4.6
	13	465.0	0.140	0.70	0.41	3.4
4 air	13	310.0	0.078	0.59	0.30	2.5
	13	387.5	0.093	0.56	0.27	2.4
	13	465.0	0.100	0.50	0.21	1.8
5*	13	232.5	0.16	1.60	1.31	11.0

Calculated values of film existance and film resistivity at the anode brush during current increase. Three contact spots assumed.

*values corresponding to last half hour of test

same brushes were used. They found the electrical conducitivity, σ_e, to be a power function of the volume fraction of silver in the brush. From this function a value for σ_e of $4.8 \times 10^6\ \Omega^{-1}m^{-1}$ (i.e. $\bar{\rho}_B = 21 \times 10^{-8}\ \Omega m$) may be inferred for the brushes considered. The contact hardness was found to be on the order of $3 \times 10^8\ N/m^2$.

Using these values and the resistivity of copper (corrected for temperature effects), $2.9 \times 10^6\ \Omega^{-1}\ m^{-1}$ for σ_R in Equation (2), the constriction resistance is found as

$$R_C = \frac{3.3 \times 10^{-4}}{n^{1/2}}\ \Omega \qquad (5)$$

TABLE 3

Fig. #	v m/s	J A/cm²	V_{drop} V	R_T mΩ	R_F mΩ	σ_F x10⁹ Ωm²
2	5.1	232.5	0.075	0.75	0.46	3.8
	5.1	310.0	0.083	0.62	0.33	2.8
	5.1	387.5	0.092	0.55	0.26	2.2
	5.1	465.0	0.112	0.56	0.27	2.3
2	26	232.5	0.070	0.70	0.41	3.4
	26	310.0	0.078	0.59	0.30	2.5
	26	387.5	0.095	0.57	0.28	2.3
	26	465.0	0.100	0.50	0.21	1.8
2	30	232.5	0.060	0.60	0.31	2.6
	30	310.0	0.078	0.59	0.30	2.5
	30	387.5	0.148	0.87	0.58	4.8
	30	465.0	0.095	0.47	0.18	1.5
2	35	232.5	0.072	0.72	0.43	3.6
	35	465.0	0.110	0.55	0.25	2.1
3	13	387.5	0.070	0.42	0.13	1.1
	13	465.0	0.085	0.42	0.13	1.1
4	13	310.0	0.110	0.83	0.54	4.5
	13	387.5	0.135	0.81	0.52	4.3
	13	465.0	0.160	0.80	0.51	4.3
4 air	13	310.0	0.042	0.32	0.30	0.25
	13	387.5	0.053	0.32	0.30	0.25
	13	465.0	0.065	0.32	0.30	0.25
4 air	13	310.0	0.041	0.31	0.20	0.17
	13	387.5	0.053	0.32	0.30	0.25
	13	465.0	0.070	0.35	0.60	0.50

Calculated values of film resistance and film resistivity at the anode brush during current decrease. Three contact spots assumed

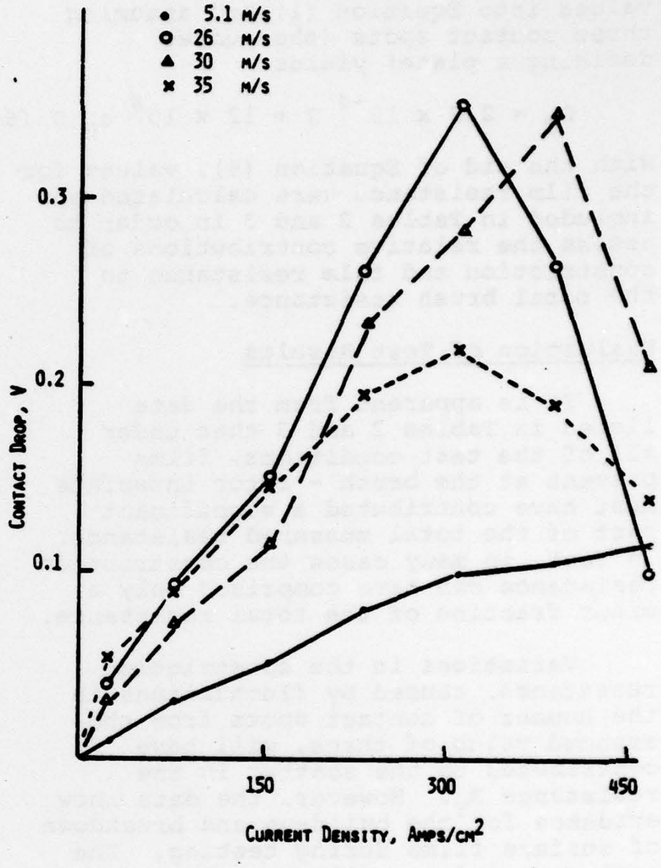

Figure 1

Electrical contact drop of anode silver graphite brush during current increase

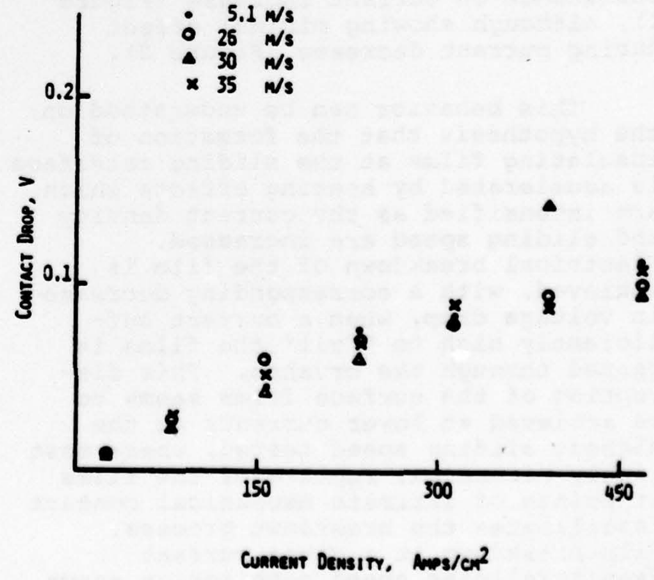

Figure 2

Electrical contact drop of anode silver graphite brush during current decrease

The calculated bulk resistance of the brush was on the order of $1 \times 10^{-4}\ \Omega$. Substituting these values into Equation (1) and assuming three contact spots (the number defining a plane) yields

$$R_T = 2.9 \times 10^{-4}\ \Omega + 12 \times 10^{6}\ \sigma_F\ \Omega \quad (6)$$

With the aid of Equation (6), values for the film resistance were calculated and included in Tables 2 and 3 in order to assess the relative contributions of constriction and film resistance to the total brush resistance.

Evaluation of Test Results

It is apparent from the data listed in Tables 2 and 3 that under all of the test conditions, films present at the brush - rotor interface must have contributed a significant part of the total measured resistance. In fact, in many cases the constriction resistance can have comprised only a minor fraction of the total resistance.

Variations in the constriction resistance, caused by fluctuations in the number of contact spots from the assumed value of three, will have contributed to the scatter in the resistance R_T. However, the data show evidence for the build-up and breakdown of surface films during testing. The most surprising result was that, consistently, film resistance was higher while the current density was being increased than when it was decreased. (See Tables 2 and 3). The surface sliding speed evidently influenced the resistance on current increase (Figure 1), although showing minimal effect during current decrease (Figure 2).

This behavior can be understood on the hypothesis that the formation of insulating films at the sliding interface is accelerated by heating effects which are intensified as the current density and sliding speed are increased. Electrical breakdown of the film is achieved, with a corresponding decrease in voltage drop, when a current sufficiently high to "frit" the films is passed through the brushes. This disruption of the surface films seems to be achieved at lower currents at the highest sliding speed tested, where most likely mechanical rupture of the films at points of intimate mechanical contact fascilitates the breakdown process. Film breakdown at a given current density/sliding speed combination seems also to be a function of time (Figures 3 and 4). However, if the current density and sliding speed are not sufficiently high to effectively disrupt the film, the voltage drop and the film resistance, remain high over long periods of time (Figure 5).

It seems likely that the film resistance itself can be divided into two components:

1. The resistance due to graphite platelets, transferred from the brush, present at the sliding interface. The graphite layer, with adsorbed layers of water and gas vapor on it, may reduce metal to metal contact at the interface causing the brushes to slide along a film layer with relatively high film resistance.

2. The resistance due to films formed on copper and silver under all circumstances (e.g. oxides, sulphides, CO_2/H_2O vapors adsorbed on the bare metal surfaces) and which presumably persist regardless of the presence or absence of the lubricant film.

Data in Tables 2 and 3 suggest that before disruption of the lubricant film takes place, the graphite film resistance is the dominant contribution to the total measured resistance. On the basis of these data, the magnitude of the residual film resistivity (comprised primarily of component 2 discussed above) is on the order of $2 \times 10^{-12}\ \Omega$, which is in good agreement with results discussed by Holm:[9]

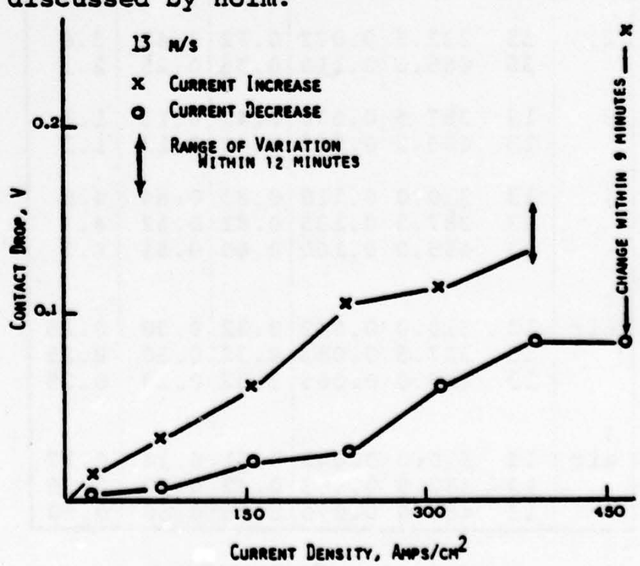

Figure 3
Electrical contact drop of anode silver graphite brush at 13 m/s

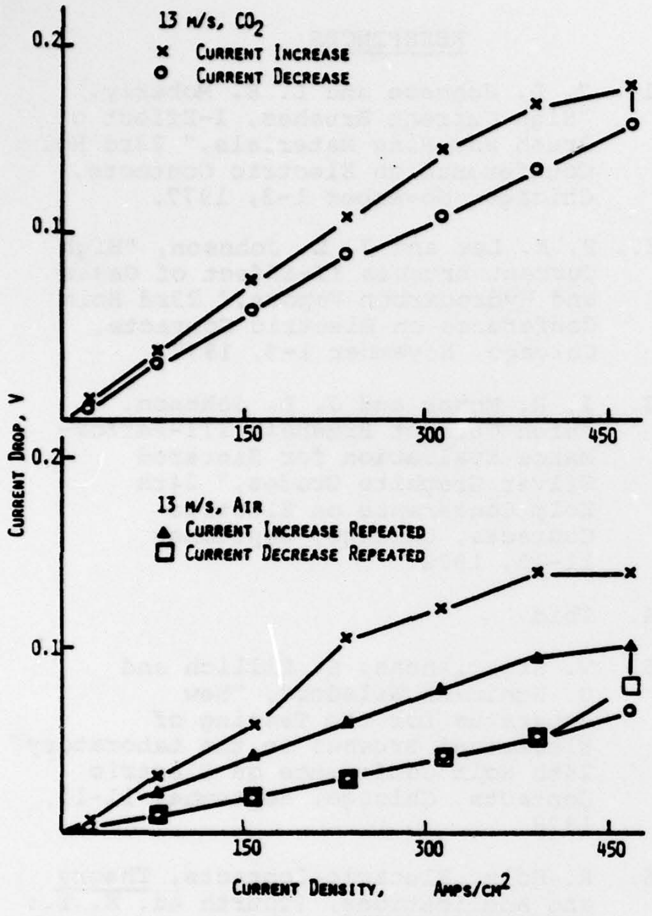

Figure 4
Electrical contact drop of anode silver graphite brush in CO_2 and in air, at 13 m/s. In air, the brushes were held at 465 Amps/cm^2 for 5 minutes before current was decreased.

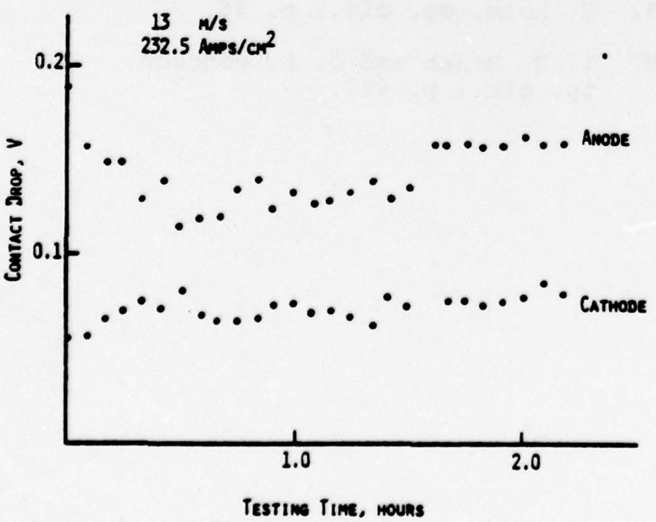

Figure 5
Electrical contact drop of silver graphite brushes tested at 13 m/s, 232.5 Amps/cm^2.

Somewhat unexpectedly, the overall brush contact resistance was found larger in CO_2 than in air, although the coefficients of friction were lower in CO_2. I. R. McNab and J. L. Johnson[10] employed a "law of mixtures" type of rule to predict a value for the coefficient of friction of silver graphite, 75 w/o Ag, brushes. Coefficients of friction listed in Table 4 are in good agreement with this predicted value of 0.18.

TABLE 4

Increasing Current			Decreasing Current		
Fig. #	v m/s	friction coeff., μ	Fig. #	v m/s	friction coeff., μ
1	5.1	0.200±.007	2	5.1	0.191±.008
1	26	0.201±.023	2	26	0.206±.008
1	30	0.219±.030	2	30	0.200±.013
1	35	0.253±.050	2	35	0.190±.050
3	13	0.160±.040	3	13	0.117±.008
4	13	0.230±.025	4	13	0.170±.015
4*	13	0.263±.005	4*	13	0.250±.002
4*	13	0.250±.008	4*	13	0.247±.005
5**	13	0.173±.005			

Average coefficients of friction for silver graphite brushes run on copper rotor.
* Tested in air (all other data in CO_2).
** Value corresponding to last half hour of testing.

CONCLUSIONS

The preceding discussion has shown that, in most instances, a significant, and often the greater part of the electrical loss was due to films thicker than the adsorption films on clean metals, which have typical film tunnel resistivity on the order of $10^{-12}\Omega\text{-m}^2$. These relatively thick films evidently were building up and breaking down depending on current density and speed, quite likely mediated by the resultant temperature at the interface.

Qualitatively, the contact behavior may be understood on the hypothesis that high temperatures initially aid in film formation but that at some critical point, determined by the simultaneous mechanical film rupture and local action of the current, the film breaks down and is then not easily reestablished at the same or lower values of the current. This is seen as the reason why on decreasing the current the voltage drop remained quite low, and in fact, occasinally became so low as to suggest that only the adsorption films typical for clean metals persited.

The brush tests have concentrated on only a rather narrow range of variables. Even so, it is difficult, and quite likely impossible, to make a predictive theory on the behavior of the films as a simultaneous function of current density, sliding speed, brush pressure, ambient atmosphere, and time. The adsorption films on "clean" metals are much more easily treated theoretically. The question raised at the outset, namely to what extent it may be possible to dispense with deliberately introduced lubrication layers, is reopened by the observation that, on current reduction, the brushes appear to have operated on occasion without interposed lubrication films at the a-spots, and to have done so with simultaneously reduced coefficient of friction.

It is an intriguing result of this study that superior brush test results were achieved at the highest current densities and sliding speeds, provided only that the films had been removed in the preceding history of testing.

ACKNOWLEDGEMENTS

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DEVELOPMENT OF HIGH-PERFORMANCE METAL FIBER BRUSHES

I - BACKGROUND AND MANUFACTURE

C. M. Adkins III and D. Kuhlmann-Wilsdorf
Department of Materials Science
University of Virginia
Charlottesville, VA 22901

ABSTRACT

On the basis of theoretical arguments, the potential improvement of metal fiber brush performance above the performance of monolithic brushes is very great. First-order theory suggests that the fiber diameter should lie between a few to perhaps one hundred microns, and the packing density between a few percent and, say, 20% at the most. Metal fiber brushes of this kind can be made by etching away the matrix material from among the fibers in filamentary materials such as are in use for superconducting devices, ultimately no doubt at modest cost. The cost of making a few small laboratory samples of the requisite multifilamentary materials by industrial processes is, however, prohibitive. Methods were therefore developed which adapt the multiple drawing and rebundling employed for superconductive multifilamentary materials to the laboratory. Brushes have so far been made with fibers of copper, gold, niobium, platinum and silver. Part II reports on their testing and properties.

INTRODUCTION

The word "brushes" for electrical current transfer between stationary and moving parts of machinery or apparatus betrays the early form of such devices, namely fiber brushes. The first relevant patent appears to be that of Thomas A. Edison[1] applied for in November 1882. There has been an impressive number of subsequent suggested improvements on "brushes," as well as related inventions which never found any significant application.

The reason for the perceived superiority of electrical fiber brushes with many separated fibers, has been well stated by Elihu Thomson[2] when he wrote in his May 21, 1895 patent application for a carbon brush: "The particular object of my invention is to improve the conductivity of the brush while preserving its elasticity and to provide a large number of contact points for the reception or delivery of current from the brush, the different parts of the brush adapting themselves by their elasticity or flexibility to surfaces which are not altogether true. Another object of my invention is to reduce to a minimum the pressure which has to be applied to the brush in order to secure sufficient contact with the commutator . . ."

The brush proposed by Elihu Thomson was already surprisingly advanced, consisting of lightly metallized carbon filaments. The widespread introduction of Edison's, Thomson's and other inventors' fiber brushes was presumably prevented by three causes. Firstly, fiber brushes tend to be much more expensive than solid, i.e. "monolithic", brushes. Secondly, the monolithic graphite brush was successively improved to the point that its losses are easily tolerable in all previously common applications, its lifetime is long, and its cost low. Thirdly, as will be shown in part II, the brush parameters (i.e., packing density, fiber diameter, brush pressure and fiber length) importantly influence brush performance, as does the ambient atmosphere. Lacking some theoretical understanding and careful experimental testing it would be difficult, to say the least, to locate optimum combinations.

During the past several years, the interest in fiber brushes has been revived on account of the development of engineering concepts and planned devices which call for very high current densities and high relative speeds, often with only small total potential differences generated, demanding much lower losses per ampere conducted than was previously permissible. The standard monolithic graphite brush cannot meet the envisaged new much more stringent requirements.

THEORETICAL BRUSH DESIGN

In its basic principle, the goal that one wants to achieve with fiber

brushes has remained the same as that indicated already by Elihu Thomson, namely to provide many contact spots on a highly conducting brush at a minimum of force between the two surfaces. Also the mechanical characteristic of the brush surface that is perceived to provide the many contact spots at small load remains unchanged, namely a high degree of compliance in the direction normal to the slip ring or commutator.

A few very simple considerations show the theoretical advantage of fiber brushes as compared to monolithic brushes: The total contact resistance between brush and slip ring consists of three major parts, namely (i) the ohmic resistance of the body of the brush, R_{Ohm}, (ii) the constriction resistance, R_{con}, and (iii) surface film resistance, R_F. The contact resistance controls the electrical loss of the brush, L_E at current I as

$$L_E = (R_{con} + R_F + R_{Ohm})\, I^2 = R_E I^2 \qquad (1)$$

or expressed in terms of voltage drop $\Delta V_E = R_E I$, measuring in effect the electrical loss per ampere conducted

$$\Delta V_E = L_E/I = R_E I. \qquad (2)$$

Often, the most important contribution to the electrical loss in monolithic brushes is that due to the constriction resistance. As shown by Holm[3] this is proportional to $n^{-\frac{1}{2}}$ if n designates the number of current carrying contact spots, i.e. a-spots. In a monolithic brush, $1 \leq n \leq 20$, with 5 a not untypical value. In a fiber brush, it is reasonable to assume that n is in the order of the number of fibers and thus can be tens of thousands, meaning that the constriction resistance may be reduced by a factor of tens, or more than one hundred, rendering its contribution to L_E negligible.

In monolithic brushes, the constriction resistance as well as the film resistance is being reduced through increasing the load, P, and hence the actual, load bearing contact area A_b. This correspondingly raises the mechanical loss, L_M, given by

$$L_M = \mu P v \qquad (3)$$

where μ is the coefficient of friction and v is the relative velocity between the two surfaces. With the total loss per ampere conducted given by

$$\Delta V = (L_E + L_M)/I = (R_{con} + R_F + R_{Ohm}) I + \mu P v/I. \qquad (4)$$

Brush loading therefore represents a compromise of reducing the electrical loss without unduly increasing the mechanical loss. Typically, at optimum running conditions, $L_E \approx L_M$ for monolithic brushes. Correspondingly, it is generally considered necessary to lubricate monolithic brushes so as to decrease μ and thus L_M. The introduction of deliberate lubrication commonly causes an increase in film resistivity, however. Lastly, the needed continuous lubrication is mostly applied by making the brush body at least partly out of graphite, which means that the ohmic resistance of monolithic brushes remains significant.

In all of these respects, the fiber brush, with fibers made out of metal, is potentially very superior. Not only is its ohmic resistance negligible, even if the packing density of the fibers is only a few to, say, 20%, at fiber lengths in the order of millimeters to 1 or 2 cm, but deliberate lubrication seems unnecessary or harmful. Namely, loads can be made so small that the value of L_M is small even if the coefficient of friction is near unity instead of 0.2 as typical for graphite brushes. In this, the required compliance of the brush in the direction normal to the rotor depends on the average fiber being bent into some radius of curvature comparable to the fiber length.

The requisite force at low enough packing density to permit independent motion of the fibers is proportional to d^4/ℓ^2, if d is the fiber diameter and ℓ the fiber length. As compared to the compliance of the solid brush, the fiber brush can thus be made elastically softer by millions choosing d/ℓ in the order of 0.01 or less, i.e. fiber thicknesses in the order of 100 microns or less. Correspondingly the brush load, being limited only by the requirement to keep the brush in place with a light elastic bending of the fibers, can in principle be made as small as one wishes. In practice, it is pointless to reduce the value of P to below about 0.2N for a brush of $1cm^2$ area, or so, since this reduces the mechanical loss to insignificant levels as compared to the mechanical loss at about $8N/cm^2$ pressure typical for monolthic graphite brushes.

Practical limitations on the fiber diameter derive from two sources. Firstly, whether deliberate lubrication is used or not, the air current about the rotor will prevent the fibers from contacting the rotor surface if the brush surface is elastically too soft. Secondly, if deliberate lubrication is used, one must suspect that too thin

fibers, pressing against the rotor with a too small force, will not penetrate the surface films. A third potential limit, namely that the a-spots must have a diameter larger than the mean free electron path, is probably of secondary interest except perhaps at low temperatures, since either of the two former considerations would seem to make fiber sizes below several microns, impractical.

In summary, then, very basic theoretical considerations suggest that metal fiber brushes with fibers between 100 and 1 micron thickness, of lengths in the order of a few millimeters to ~2cm, and with packing densities between a few percent to, say, 15% (or up to 20% depending on the friction between neighboring fibers), should be greatly superior to monolithic brushes, provided that they are properly constructed and run. The requisite running conditions include a light load well below that employed for monolithic brushes. With regard to the construction, one prefers to reduce friction among the fibers since otherwise the brushes will not permit the fibers to flex individually. This means that one should strive for smooth, evenly spaced fibers. These, at the least, are the conclusions based on the above simple considerations. In order to test those conclusions, metal fiber brushes of the discussed type have been made and tested.

MANUFACTURE OF METAL FIBER BRUSHES

Making fiber brushes is a rather straightforward process as long as the fibers, or wires, are fairly thick, say 100 microns or more, namely via the mechanical assembling of bundles of fibers like ordinary brushes. In that case one may begin with already assembled wire or fiber materials such as grounding cables, spooled wire or fibers, or woven material out of which the weft, say, is removed, leaving only the warp. With carbon fibers such methods are also feasible down to much smaller diameters since these are commercially available at relatively modest cost including diameters in the order of 10 microns. With metals, however, the cost of wire material rises very steeply with decreasing diameters and the price of brushes made by any of the above approaches becomes entirely prohibitive if, say, 50 μm and thinner fibers are wanted. Another grave disadvantage of mechanical methods of brush making using metal fibers of small diameters is the difficulty of reliably adjusting the packing density on a small scale, as well as shaping the brush surface to conform to the rotor diameter and angle of attack of the brush. The latter is not much of a problem if the packing density is high, say, 20% and higher, since at such packing densities the internal friction among the fibers renders the brush quite stiff. However, what is wanted is a very pliable brush surface, and for a "metal velvet", unlike textile velvets, there is no known method of "shearing".

For these reasons it was considered necessary to begin with some suitable multi-filamentary material and, after shaping the contour of the future brush, to etch away the matrix material leaving the filaments exposed. Here, again, a choice may be made as how to procure the necessary multi-filamentary material. The first thought which comes to mind is, naturally, to employ multi-filamentary materials such as are widely used for super-conducting wires. The filaments in these can be as thin as a few microns and the cost of the material is moderate. In this much, then, commercial superconductor multi-filamentary materials would seem to be an excellent choice. However, they are available only in a very narrow range of filament material, - overwhelmingly niobium -, which is very restrictive. Also, the material is generally made with high packing densities and often incorporates "shields", e.g. of tantalum, which make the subsequent etching process rather difficult. Lastly, these materials are often cabled or twisted in their interior structure. For purposes of making metal fiber brushes this is undesirable, though not critical, since it imparts high internal friction to the brush.

The next approach would logically be to employ the same technique by which the superconducting multi-filamentary materials are made, and to design one's own combination of matrix/fiber materials, fiber diameter, and packing density. This is practically impossible because the machinery needed is very expensive (much is done with large extrusion presses). Nor can one purchase the needed material commercially at reasonable cost since the specific methods, i.e. degree of drawing between anneals etc., need to be tried out separately from case to case, and the minimum amount of material processed in the industrial method is much too large for the use of somewhat scarce or precious materials such as silver, gold etc. Correspondingly, it would take weeks and would cost thousands of dollars to procure each different multi-filamentary sample material.

Next there is the possibility of making the required samples in the laboratory by extruding, swaging, rolling,

and/or drawing down suitable materials which are fine mixtures of the intended matrix and filamentary metals. If the degree of diameter reduction is high, long filaments will be made even from spherical particles and thus it is possible to begin with mixtures of metal powders,[4-7] directionally solidified eutectics,[8,9] or directionally rapidly solidified melts of metals immiscible in the solid state.[10-12] Investigations on samples of such materials revealed that they are unsuitable, mainly for the reason that the filaments are much too irregular in shape and too short for our purposes. The directionally solidified materials have the further disadvantage that the choice of materials combinations and packing densities is very restricted.

Another possibility that is very promising in principle is the use of polycrystalline (Schladtiz) whiskers of iron or nickel[13,14] infiltrated with another material . The difficulty in this case has so far been that no method was found to embed the whiskers in a matrix material which could be subsequently etched away without either bunching them together (which occurs if the matrix material does not wet the whiskers well) or dissolving them (as is happening with most wetting infiltrants). However, the investigation is continuing and there is some hope that it will lead to success.

The method which has been successful and was adopted in this research is that of successively drawing and rebundling wires. It resembles the method used industrially for the production of superconducting multi-filamentary materials, but using laboratory equipment and is an adaption of the methods developed by Stöckel[7,15,16] who, however, had available for his use much machinery and know-how of a specialty industry.[17] It consists of the encasing of wires in tubing, drawing down in stages, rebundling in tubing, and drawing down again.

A selection of samples kindly supplied by D. Stöckel was not of practical use to us for the same reasons mentioned already in connection with superconducting multi-filamentary materials: The requirements for starting stock for metal fiber brushes in regard to the fiber/matrix materials combination, fiber diameter, and packing fraction are too specific as that they would accidentally be met by materials made for other purposes. Still, the samples received from D. Stöckel showed that the method works in principle, and it was possible to develop laboratory techniques to duplicate them with hand labor and simple equipment, primarily a car winch mounted on an I-beam, and a set of drawing dies. The specific know-how involved in making any particular kind of fiber brush is one of experience, rather than principle, e.g. it must be determined to what degree a compound can be drawn before it develops internal fractures, in what stages it can be drawn, what are appropriate annealing temperatures and times, at what stage is it best to rebundle, and what is a good lubricant in the dies for a specific material.

In the most successful method, the first stage is the encasing of a single wire in tubing of the matrix material. In another variant, which is faster, one begins with the mixture of wires of the

Figure 1: Several individually cased gold fibers in a copper matrix.

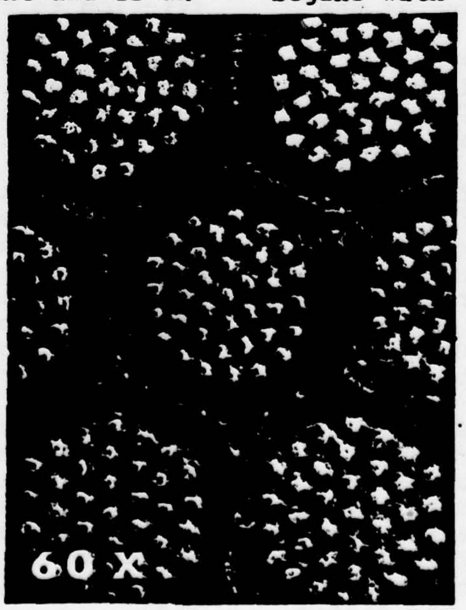

Figure 2: Secondary bundles of gold fibers in copper matrix.

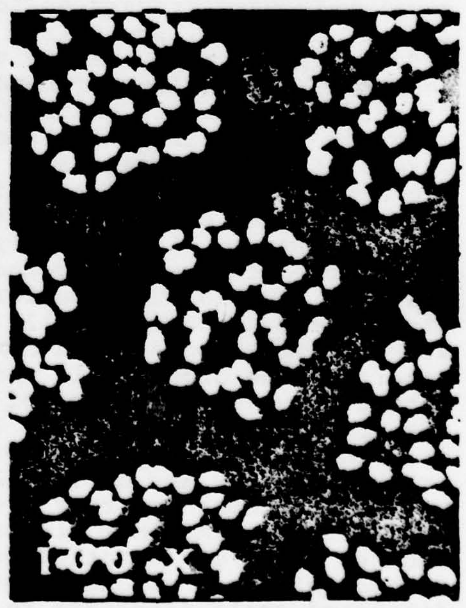

Figure 3: Bundled mixed gold and silver fibers producing greater distortion.

filament and matrix materials in a tubing of the matrix material. As shown in Figs. 1 to 3, the latter method yields more severely distorted filament cross sections, and it was not further used for that reason.

The choice of matrix and filamentary materials combinations (but not the packing density) is somewhat restricted for three reasons. Firstly, the hardnesses of the two materials should best not be too different so that they draw down well together. Secondly, they should not be too readily soluble at their recrystallization temperature so that the filaments do not dissolve in the matrix during intermediate anneals. Thirdly, it must be possible to etch away the matrix and leave the filaments untouched in the final step of making the brush. Correspondingly, only some combinations have so far been tried successfully, including filaments of gold, silver, platinum and niobium in copper, and of copper in aluminum.

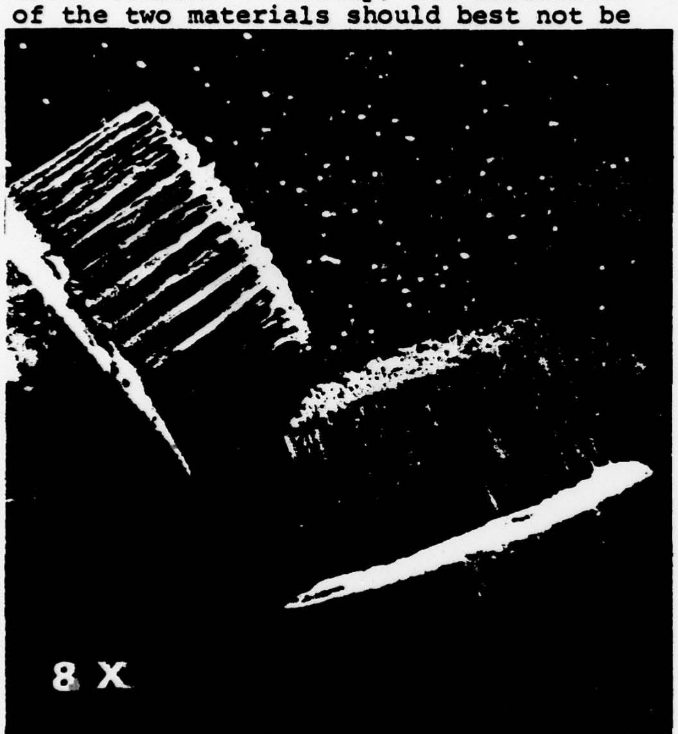

Figure 4: Ready-to-run silver fiber brushes. Fiber diameter 18μm, packing fraction 8.9%, brush area 0.62cm^2.

Figure 4 shows a pair of brushes ready to be tested.[18] The results obtained and their theoretical interpretation are the subject of part II.

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DEVELOPMENT OF HIGH-PERFORMANCE METAL FIBER BRUSHES

II - TESTING AND PROPERTIES

C. M. Adkins III and D. Kuhlmann-Wilsdorf
Department of Materials Science
University of Virginia
Charlottesville, VA 22901

ABSTRACT

Metal fiber brushes as described in Part I have given excellent results when tested at light loads against stationary surfaces as well as within a wide range of relative speeds. At a load between 0.1 and 0.2 N (about 0.5 oz) the static contact resistance against a clean, polished copper surface was ~ 1.6×10^{-4} Ω for a surface of ~ 0.1 in^2 ≈ 0.7 cm^2. When the brushes are run in an argon atmosphere they exhibit a constant contact resistance of a few tenths of a milliohm at speeds up to 35 m/sec and current densities up to $6.5\times10^6 A/m^2$ ≈ 4000 A/in^2, which were the limits of testing capability. Under the most favorable conditions located yet, namely a brush pressure of several thousand N/m^2, a copper rotor with a gold - carbon surface treatment, and a moist argon atmosphere, the sum of mechanical and electrical loss at 6.5×10^6 A/m^2 and 35 m/sec amounted to ~ 0.1 watt per ampere conducted per brush. This is much superior to the performance of the best commercially available brushes. The relative performance advantage of the brushes is equally large at low current density and low speeds, as for stationary contacts at low loads. The results are fully understood on the basis of contact theory. These findings promise a significant advance in brush and contact technology.

INTRODUCTION

Metal fiber brushes, with fiber diameters from a few microns to 120 μm, and packing densities between a few % and up to 20%, have been made of various materials by the method discussed in part I. They were tested using apparatus described previously[1] improved by the inclusion of a modified brush holder and loading device.

In the improved device, rather than monitoring the position of the brush relative to the rotor by means of a linear differential transducer and reading the compression of the loading spring by eye, the transducer is employed to monitor the compression of the spring, thereby achieving a much more accurate load determination. By advancing the brush via a micrometer head so as to keep the spring compression, and hence the load, constant, the brush wear may be determined continuously to the reading accuracy of the micrometer head. Further, the linear bearings guiding the brushes have been replaced by one pair each of the best linear bearings available. With these improvements, the apparatus is now easily adequate to all reasonable requirements.

Brushes with gold, platinum, niobium and copper fibers have been tested, - the latter two kinds only very sketchily. Since the most complete and systematic set of data available so far has been obtained with gold fiber brushes, these shall be discussed primarily. Throughout, great care was taken to achieve the greatest possible degree of reproducibility by observing well-defined and clean experimental conditions. Measurements were made in relatively dry (humidity somewhat below 30%) and moist (humidity somewhat above 80%) argon, and in two load ranges, namely loads under which the brushes did not suffer significant permanent deformation as macroscopically observable, and loads which caused distinct plastic deformation of the brushes. As will become clear later in this paper, the behavior of the individual a-spots is elastic in both cases, however.

MEASUREMENTS

Static Contact Resistance

Measurements of static contact resistance of three different pairs of gold brushes against a carefully cleaned and polished copper rotor have proven to be most informative. The brushes had fiber diameters, packing fractions, and brush areas, as given in Table I. Their contact resistances in a range of light loads are plotted in Fig. 1.

TABLE I

#	Symbol	Fiber Diameter, d	Packing Fraction, f	Brush Area, A_B
1	●	20 μm	10.5 %	0.80 cm^2
2	◉	22 μm	15.5 %	0.77 cm^2
3	★	100 μm	9.7 %	0.64 cm^2

Table I: Geometrical data for the brushes to which Fig. 1 pertains.

The contact resistances for brushes 1 and 2 fall into the indicated scatter band about 1 to 3×10^{-4} Ω and thus are considerably lower than the contact resistances of very clean crossed copper rods at same loads.[2] However, while still remarkably low, the contact resistances of brush 3, with the thicker fibers, are roughly two times higher than for the brushes with the 20 to 22 micron fibers. The interpolation

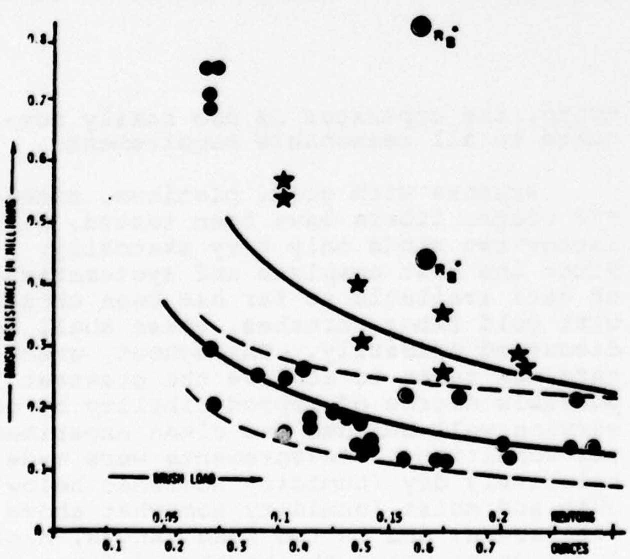

Figure 1: Resistances of the brushes listed in Table I in the static (R_B) and dynamic (R_B^*) cases. Argon atmosphere with <30 % humidity. Interpolation curves are derived from eqs. 10, 11 and 19-23 with $\sigma_F=5\times10^{-13}\Omega m^2$, $\alpha=3$, r_{Au} equal to fiber radius, $r_{Cu}\approx100\mu m$. The R_B^*/R_B values imply $\alpha^*\approx1$, as predicted.

curve to brushes 1 and 2 was used to determine the numerical parameters in the theory discussed further on. The curve to brush 3 is also consistent with theory.

Qualitatively, the dependence of the contact resistance on fiber diameter could be explained in terms of constriction resistance, since the brushes with the thinner fibers offer the larger number of a-spots. However, in accord with the discussion in Part I, the constriction resistance of the fiber brushes must be negligibly small and the observed contact resistance must be film resistance. First-order theory for plastically deformed a-spots predicts independence of the film resistance from brush geometry on the grounds that the current-carrying contact area is directly determined by the hardness, H, of the material, and the applied load, P. Namely,[3]

$$A_b = P/\xi H \qquad (1a)$$

where the parameter ξ can vary between unity and about 0.05 with a most frequent value in the range about 1/3, provided that the a-spots are completely plastic.

If, contrary to reason, the contact resistances in Fig. 1 were to be interpreted in terms of constriction resistance, they would imply between one and about ten a-spots, i.e. numbers quite comparable with typical solid contacts. However, the number of a-spots for the fiber brushes range into the many thousands. It is therefore clear that film resistance is the deciding parameter and must account for practically all of the observed contact resistance. In this connection, it may be of interest that even in the case of the crossed clean copper rods investigated by Holm, to which reference was made above,[2] the film resistance accounted for roughly three quarters of the total resistance even though only one a-spot was assumed.

Computing the total a-spot area with the aid of eq. 1a, choosing ξ = 1/3 and $H = 6\times10^8$ N/m² as appropriate for copper and gold, one obtains

$$A_b \approx (5\times10^{-9}\ m^2/N)\ P(N) \qquad (1b)$$

where P (N) is the applied load measured in newtons. Assuming that the number of contact spots is comparable to the number of fibers, the average a-spot diameter would be found from eq. 1b in the order of a few thousand angstroms.

If eq. 1a were applicable, i.e. if the a-spots were plastically deformed, the film resistance would be given by

$$R_F = \rho_t t/A_b = \rho_t t\xi H/P \qquad (2a)$$

i.e.

$$R_F = \rho_t t(2\text{x}10^8\ N/m^2)/P(N) \quad (2b)$$

where ρ_t designates the film resistivity and t the film thickness. Note, however, that for the film thicknesses concerned, tunneling and not ordinary conduction is the mechanism of current transport, meaning that ρ_t is not a constant but increases steeply with film thickness, t. Since the data in Fig. 1 are (barely) consistent with

$$R_F = (2\text{x}10^{-5}\ N\Omega)/P(N) \quad (3)$$

it would thus follow from eqs. 1 to 3 that the tunnel resistance, $\sigma_F = \rho_t t$, equals

$$\sigma_F = \rho_t t \approx 10^{-13}\ \Omega m^2 \quad (4)$$

This value is much smaller than the value of $1.5\text{x}10^{-12}\Omega m^2$ given by Holm[2] for the tunnel resistance of thin copper films. Indeed, it is much smaller than any tunnel film resistance that ever seems to have been measured. Furthermore, as may be seen from the interpolation curve in Fig. 1, the inverse proportionality between contact resistance and load predicted by eq. 1 is very poorly obeyed. Instead the contact resistance appears to vary as $P^{-2/3}$ which, as will be fully discussed in the section on theoretical interpretation, is the hall-mark of film resistance with elastic behavior of the a-spots, while eq. 1 pertains to fully plastic a-spots. Since in elastic behavior the contact area can be rather larger than for plastic a-spots, the too low value of the tunnel resistance obtained is partly explained thereby. Even so, the film resistance is indeed very low, largely thanks to the favorable choice of atmosphere.

Brush Performance Under Macroscopically Elastic Loading

The gratifyingly low level of the static contact resistance documented in Fig. 1 finds its counterpart in similarly low levels of the contact resistance when the brushes are run against a moving rotor. However, contrary to the expected behavior of solid, i.e. monolithic, brushes, the electrical loss of the fiber brushes is two to three times larger when running as compared to the static contact resistance. Very surprisingly under these circumstances, the brush resistance does not depend on rotor speed, though.

Besides low electric loss, to be considered in greater detail below, the fiber brushes have at least two other strong advantages. Firstly, the loads at which these brushes can (and should) be run are well below those appropriate for monolithic brushes, as was already explained in Part I, whence the mechanical loss is correspondingly much lower. Secondly, the brushes run very quietly in the radio frequency region, although there remain voltage fluctuations caused by irregularities in the rotor surface which are known also from traces of monolithic brushes. It appears to be a third considerable advantage that one may dispense with extraneous lubricants when using fiber brushes. As will be seen, the resulting film resistance is very low indeed, and the films of, say, two monomolecular layers of adsorbed molecules are evidently very stable with uniform properties, unlike films formed through deliberate lubricating layers.

On account of the low brush loads, the rotor surfaces appear not to suffer any mechanical damage. Fig. 2 compares the surface roughness of a rotor surface before and after a fiber brush has been run on it. To be sure, more sensitive investigations will doubtlessly reveal some differences, especially since visually the brush track can be seen by a changed coloration. However, the surface profile appears to be remarkably little affected by the brushes, a feature which plays some role in the theoretical interpretation.

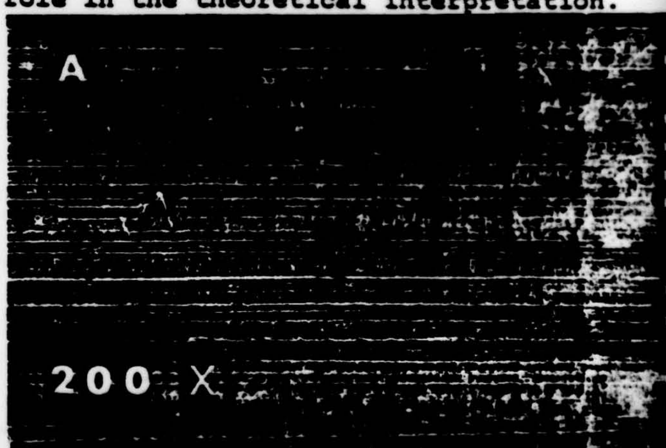

Figure 2: Micrograph of a copper rotor surface (a) before and (b) after a gold fiber brush has been run on it. As will be seen, the surface topology has not been noticeably changed.

Contact theory, to be discussed below, accounts for the observed dependence of brush resistance on the geometrical parameters, including fiber diameter, packing fraction and brush area, in microscopic terms. On the macroscopic level, these same parameters play an additional, independent role, in that they control the compliance of the brush surface and thus the lower limit of the loads required to ensure smooth running, as also to some extent brush wear and the upper limit of velocity to which the brushes can be run at a given speed. These features will become clearer by considering the experimental results obtained with the brushes.

Figs. 3 to 5 illustrate the effect of fiber thickness and packing density on the characteristics of otherwise similar brushes, i.e. brushes with similar fiber lengths and overall brush area, A_B. They are the same as listed in Table I with the addition of a 120 μm fiber diameter brush with 19.6% packing density. In each case the velocity is 13 m/sec and the atmosphere is low-humidity argon, and all are run against a clean polished copper rotor of the same diameter. For comparison purposes, the best data obtained with a monolithic 75w% silver-graphite brush (Stackpole SG-142) have been included as this seems to be the best commercially available brush at this time.[4,5]

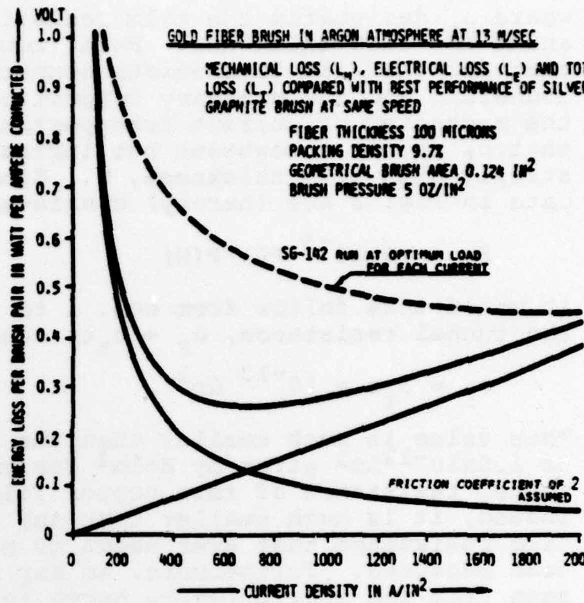

Figure 4: As Fig. 3 but for 100 μm fibers and f = 9.7% packing density. As in Fig. 1, the resistance is ~ 2x that of brushes 1 and 2 (comp. Fig.3).

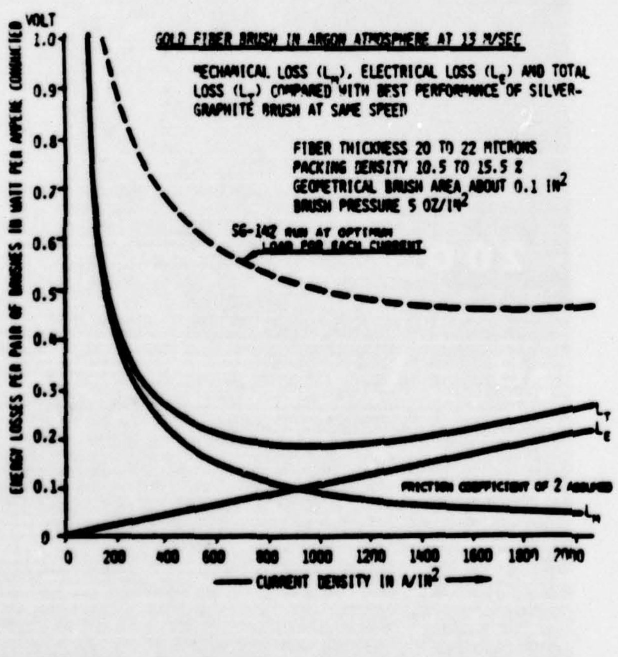

Figure 3: Performance of gold fiber brushes, elastic loading, 13 m/sec velocity. Brush pairs #1 and 2 of Table I (20 and 22 μm) give very similar results, in spite of different packing fractions. Theory predicts their brush resistances to differ by 6%. Argon with 30% humidity.

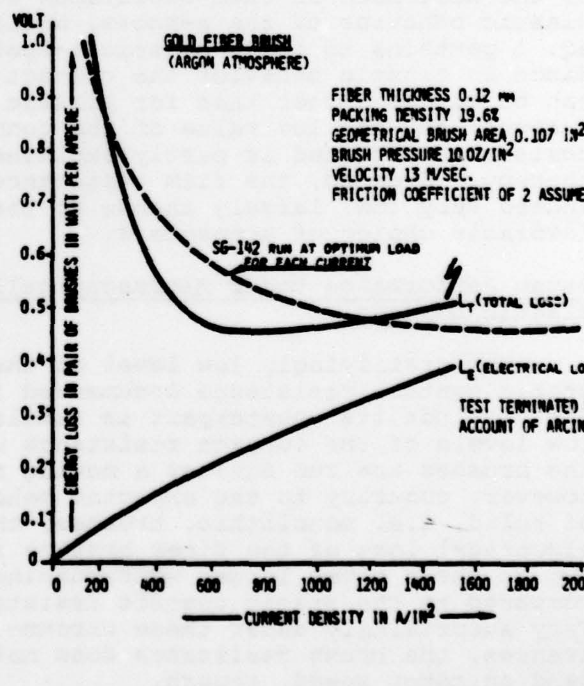

Figure 5: As Fig. 3 but for 120 m fibers, higher load, and f = 19.6%.

The performance of the brushes with fiber diameters about 20 μm (Fig. 3) is

clearly very superior to the SG-142 brushes. It is also noticeably superior to that of the 100 μm brushes (Fig. 4), the same brushes listed as #3 in Table I. Fig. 5 shows that a fiber diameter of 120 μm at 19.6% packing density, however, yields much less favorable results and indeed requires a higher brush load even to keep from sparking. This is a consequence of the too great stiffness of the brush.

Figs. 3 to 5 show the mechanical as well as the electrical and total loss in volts, i.e. in terms of power loss (in watts) per ampere conducted. The current density is, of course, computed for A_B, the macroscopic brush area, i.e. the area which the brush occupies on the rotor. The current density through the individual fibers is higher than the overall current density by the factor 1/f, if f designates the packing fraction.

Due to technical difficulties, which were subsequently removed, the mechanical loss could not be experimentally determined in the cases of Figs. 3 to 5. It was calculated assuming that the coefficient of friction was 2.0. This is a deliberate overestimate, so as to be sure not to make any inflated claims. The actual mechanical loss was probably only a quarter of this, consonant with the subsequently measured coefficient of friction of just under 0.5.

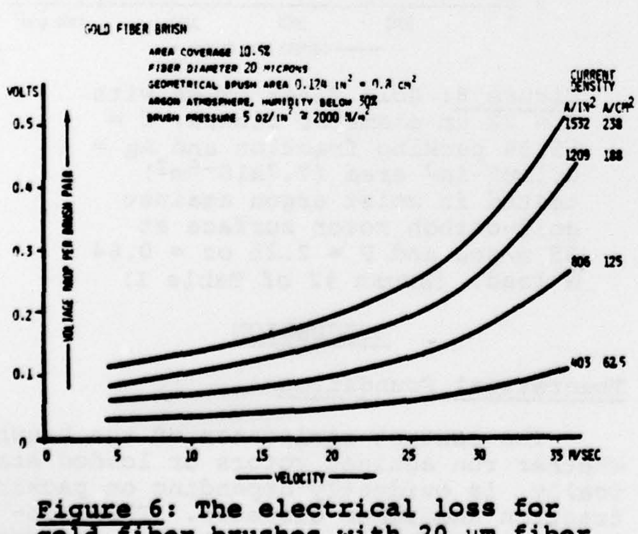

Figure 6: The electrical loss for gold fiber brushes with 20 μm fiber diameter and 10.5% packing fraction as a function of speed for different current densities. (Brush #1)

Brush Performance Under Macroscopically Plastic Loading

As demonstrated in Fig. 1 and Figs. 3 to 5, in the macroscopically elastic range of brush loading, thinner fibers yield better performance than thicker fibers, for stationary contacts as well as at a speed of 13 m/sec. It is further clear from Fig. 5 that, under these conditions at the least, packing densities too high to permit relatively independent motions of individual fibers are detrimental. These results are supplemented, and somewhat modified by the measured electrical losses as a function of rotor velocity and current density, as depicted in Figs. 6 and 7. They reveal a highly unwelcome aspect of the very light loading, namely that the electric loss increases with increasing rotor velocity, the more so, the thinner the fibers. In view of the goal of developing brushes usable at high current densities to very high speeds, which motivated the present research, this is disturbing. Indeed, Figs. 6 and 7 suggest that at a velocity of about 45 m/sec, the thicker fibers will surpass the performance of the 20 μm fibers.

Contemplating this behavior, it seemed extremely improbable that the film resistivity, σ_F, changes with speed in such a peculiar manner. Certainly, compared to the electronic processes at the interface the velocities at issue are very small indeed, and similarly the a-spot diameters are very small compared to the fiber diameters. Therefore, the obvious hypothesis for the explanation of the observed velocity dependence of brush resistance is

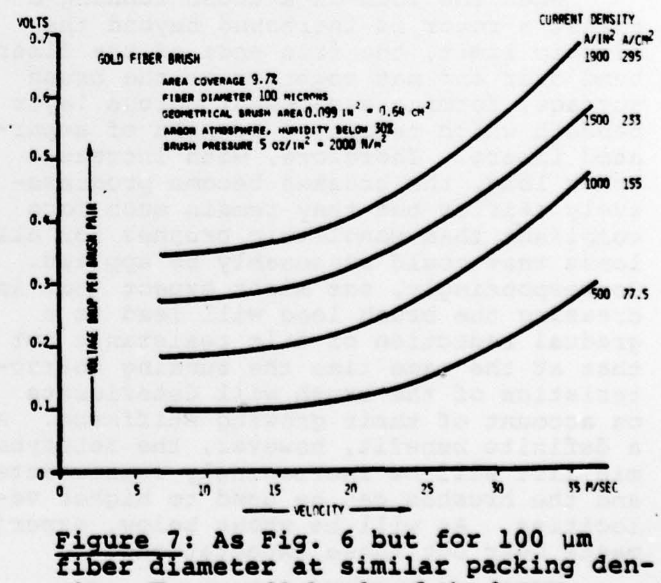

Figure 7: As Fig. 6 but for 100 μm fiber diameter at similar packing density. The overall levels of the losses are higher than for the thinner fibers but the increase with velocity is less. (#3)

that the effective load between brush and rotor drops as the fibers are lifted off the rotor aerodynamically, the thinner fibers more so than the thicker fibers on account of their greater flexibility.

Two remedies come to mind. Firstly, one might reduce the ambient pressure and, in the extreme case, run the brushes in a vacuum. This is technically somewhat difficult and might be yet less acceptable in actual technological applications. Perhaps even more importantly, while in a vacuum the lift would be removed, so would be most surface films which now protect the brushes against wear. Correspondingly, in a vacuum, aerodynamic lift and contact resistance are liable to drop dramatically, but brush wear and coefficient of friction are liable to rise to unacceptably high levels. Still, somewhat reduced pressures may eventually turn out to be excellent brush environments.

The second remedy against aerodynamic lift is an increase of the brush load so as to counteract it. The difficulty in this regard is that it is impossible to increase brush loading to any major extent beyond that required for smooth running without exceeding the elastic limit of the brushes. However, the plastically undeformed state of a fiber brush is not sacrosanct. Indeed, it is not clear a priori, whether the optimum load at which to run fiber brushes lies above or below the elastic limit. Namely, higher loads will increase the actual contact area and thereby reduce the electrical loss even while increasing the mechanical loss and impairing the compliance of the brush.

When the load on a brush running against a rotor is increased beyond the elastic limit, the free ends of the fibers bend over and mat together at the brush surface, forming a somewhat porous layer beneath which remains a cushion of separated fibers. Therefore, with increased brush load, the brushes become progressively stiffer but they remain much more compliant than monolithic brushes for all loads that could reasonably be applied. Correspondingly, one might expect that increasing the brush load will lead to a gradual reduction of film resistance but that at the same time the running characteristics of the brush will deteriorate on account of their growing stiffness. As a definite benefit, however, the aerodynamic lift will be increasingly counteracted and the brushes can be used to higher velocities. As will be shown below, experiments bear out these expectations.

The recognition of the decisive importance of the film resistance opens the door also to a purposeful search for optimum conditions of atmosphere and surface treatment. These remain as the only variables which can affect the film resistance in a beneficial manner beyond the already excellent state obtained. Manipulation of the atmosphere and surface conditions is nothing new, of course (e.g. refs. 5,6). The difference now is that one knows that one wants to influence nothing but the contact area and tunnel resistivity, and that neither the constriction resistance nor the ohmic resistance plays any significant role. Thus the search can be more purposeful.

A variety of measurements performed with brushes loaded into the plastic range bear out all of the above conclusions. They are summarized in Table II and a further, more detailed example of one particular case is given in Fig. 8.

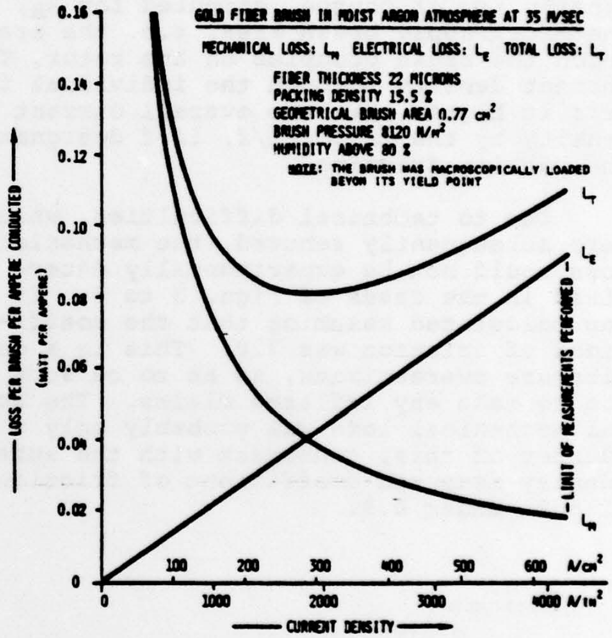

Figure 8: Gold fiber brush with d = 22 μm diameter fibers, f = 15.5% packing fraction and A_B = 0.1195 in^2 area ($7.7 \times 10^{-5} m^2$) tested in moist argon against gold-carbon rotor surface at 35 m/sec and P = 2.25 oz = 0.64 N load. (Brush #2 of Table I)

DISCUSSION

Theoretical Foundation

The contact resistance of the brushes, whether run against rotors or loaded statically, is evidently depending on packing fraction and fiber diameter. This violates first-order contact theory as exemplified by eq. 1. It could be argued that changes in the parameter ξ might offer an adequate explanation. However, this is a too simple approach for the reason that eq. 1 applies only to completely plastically deformed contact spots, while the number of a-spots in fiber brushes must be comparable to, or larger than, the number of fibers, and the loads are very light.

TABLE II

#	Rotor Surface	Humid-ity	Load, P oz	N	Pressure, P/A_B oz/in^2	N/m^2	Resistance R_B^* [Ω]	PR_B^* NΩ	$R_B^* P^{2/3}$ ΩN$^{2/3}$	$\Delta V p_B^{2/3}/J$ N$^{2/3}$m$^{2/3}$V/A
1	Copper	<30%	2.25	0.626	18.8	8120	5.83×10^{-4}	3.65×10^{-4}	4.27×10^{-4}	1.81×10^{-5}
2	Au - C	<30%	1.50	0.417	12.6	5410	5.65×10^{-4}	2.36×10^{-4}	3.15×10^{-4}	1.34×10^{-5}
3	Copper	<30%	0.60	0.167	5.0	2160	4.45×10^{-4}	7.43×10^{-5}	1.35×10^{-4}	5.73×10^{-6}
4	Au - C	<30%	2.25	0.626	18.8	8120	3.82×10^{-4}	2.39×10^{-4}	2.78×10^{-4}	1.18×10^{-5}
5	Au - C	>80%	1.50	0.417	12.6	5410	3.57×10^{-4}	1.49×10^{-4}	1.99×10^{-4}	8.47×10^{-6}
6	Au - C	>80%	2.25	0.626	18.8	8120	2.62×10^{-4}	1.64×10^{-4}	1.92×10^{-4}	8.17×10^{-6}

Table II: Results of six runs under different atmospheres, rotor surfacing and brush loads. The brushes had 22 μm gold fibers at a packing density of 15.5% on a brush area of 0.1195in^2= 7.7×10^{-5}m^2 so that each brush had N = 31,354 fibers. Fiber lengths were about 0.4 cm ≈ 0.16 in. The brush resistance remained very nearly constant in the range of measurement (up to more than 4000 A/in^2 namely 6.5×10^6 A/m^2 in the most favorable cases). Also, in all but case #3, the resistance remained constant at speeds up to 35 m/sec. The gold-graphite surfacing was specially applied to the rotor by the AMP Corporation. No differences existed between anodic and cathodic behavior. Case #1 is somewhat irregular. This occurred because the brushes had been taken out for examination and been reinserted for this run. According to theory the values in the last two columns should be constant for same atmosphere and rotor surface.

Correspondingly, the assumption that the a-spots in fiber brushes are plastically deformed is unrealistic. The opposite assumption, namely that the a-spots behave almost completely elastically, is much more reasonable.

In elastic loading, the radius of the average load bearing contact spot, r_b, is related to P_b, the load supported by the contact spot, as

$$r_b \approx 1.1(P_b r_c/E)^{1/3} \tag{5}$$

where E is the weighted average of Young's modulus of the two contacting materials, and r_c is the radius of curvature of the asperity which causes the contact spot. In equation 5 it is assumed that the asperity responsible for the contact spot is of the harder material, and that the opposing surface of the softer material is ideally flat. In fact, the numerical value of the factor which is given as 1.1 in eq. 5 involves the radius of curvature as well as the magnitudes of Poisson's ratio of both materials. Thus this factor may vary somewhat, but rarely by even as much as the factor of two.

The sum of the loads borne by all contact spots is the total load, P, and the area of all load bearing contact points is the total mechanically contacting area, A_b. Therefore,

$$P = nP_b \tag{6}$$

and

$$A_b = n\pi r_b^2 \tag{7}$$

if n is the number of contact spots. Assuming that on the average there are α contact spots on each of the N fibers in a brush of geometrical area A_B, it is

$$n = \alpha N = 4\,\alpha f A_B/\pi d^2 \tag{8}$$

with f the packing fraction and d the fiber diameter.

From eqs. 5 to 8 follows

$$A_b/A_B = \frac{1.1^2\pi n}{A_B}\left[\frac{Pr_c}{nE}\right]^{2/3} = \frac{1.1^2\pi n^{1/3}}{A_B^{1/3}}\left[\frac{p_B r_c}{E}\right]^{2/3} \tag{9a}$$

with $p_B = P/A_B$ the brush pressure. By the use of eq. 8 and collecting numerical parameters this can also be written as

$$A_b/A_B = [70\alpha f(r_c/d)^2(p_B/E)^2]^{1/3} \tag{9b}$$

Usually it is assumed that the mechanically contacting area is also the area through which the current flows, assuming that there are no insulating films. For the present purposes, on account of tunneling about the periphery of the contact spots, it is necessary, however, to distinguish A_t, the total current-carrying area, namely $A_t = n\pi r_t^2$, from the load bearing area, A_b, and permit that in general they are related as

$$A_t = K^2 A_b \tag{10a}$$

i.e. the average corresponding radii as

$$r_t = K r_b \tag{10b}$$

with $K \geq 1$. With this convention, and employing eq. 9b, the brush resistance, R_B, is related to the measured voltage drop, ΔV, at current density, J, as

$$R_B = \Delta V/I = \Delta V/JA_B = \sigma_F/A_t = (\sigma_F/A_B K^2)[(d/r_c)^2(E/p_B)^2/(70\alpha f)]^{1/3} \tag{11a}$$

where σ_F is the tunnel resistivity introduced in eq. 4. Eq. 11a may also be written as

$$\frac{\Delta V}{J} p_B^{2/3} = R_B A_B p_B^{2/3} = (\sigma_F/K^2)[E^2 d^2/(70\alpha f r_c^2)]^{1/3} \tag{11b}$$

Evaluation of Parameters

The above simple theory has three important obvious aspects. Firstly, the power loss per ampere conducted, i.e. ΔV, is proportional to the current density. Hence the brushes act as if they had an ohmic resistance independent of the current density in agreement with observation. Secondly, the loss per ampere conducted per unit area, i.e. $\Delta V/J$, decreases with brush pressure, as $p_B^{-2/3}$. Third, the power loss per ampere conducted, as well as the power loss per ampere conducted per unit area, is a function only of the material and construction of the brush but not its area nor the brush load. Thus scaling up and down of brush size is directly possible, whereas with brushes in which the a-spot resistance plays a significant role this is not the case. The only practical limitation is that the cooling has to be adequate to prevent overheating.

Before evaluating the various parameters involved in the theory, i.e. A_b, A_t, K, r_b, r_c and r_t, it is reassuring that the data are showing the predicted dependence on brush pressure. This is demonstrated in Fig. 1 by the curve

$$R_B P^{2/3} = 5\text{x}10^{-5}\ \Omega N^{2/3} \tag{12a}$$

which has been drawn into Fig. 1 and evidently is in fine accord with the pressure dependence of the brushes with 20 and 22 µm fiber diameter. Similarly, the last two columns in Table II should be constant for the same conditions of rotor surface and ambient atmosphere. With the exception of case #1 this is adequately obeyed.

For the numerical evaluation of the various parameters, it may be most convenient to begin with eq. 12a extracted from the stationary contact resistances (Fig.1), and compare it with eq. 11b. With the pertinent values of $E = 9\text{x}10^{10}\text{N/m}^2$, $d = 2\text{x}10^{-5}\text{m}$, $f = 0.1$, and $\alpha = 3$, one obtains

$$\sigma_F = R_B P^{2/3} K^2[(70\alpha f A_B)/(d^2E^2)]^{1/3} r_c^{2/3} = 4\text{x}10^{-10} K^2 r_c^{2/3} \tag{12b}$$

At this point it is necessary to make some choice of value for σ_F. Holm[8] quotes $\sigma_F = 5\text{x}10^{-13}\Omega\text{m}^2$ for contacts between clean gold surfaces in an oxygen-free atmosphere. This appears to be about the lowest realistic value of the tunnel resistivity which one might expect under the experimental conditions used. It is believed to be due to two monolayers of adsorbed molecules. A still thinner film would presumably not have as constant characteristics as may be inferred from the constancy of the observed brush resistance within a wide range of velocities and current densities, and also it would probably give rise to considerable wear. Assuming, then, that $\sigma_F = 5\text{x}10^{-13}\Omega\text{m}^2$, the radius of curvature at the contact spots is found from eq. 12b as

$$r_c = 4.5\text{x}10^{-5}/K^3\ [\text{m}] \tag{13a}$$

The ratio A_t/A_B may be found from $R_B = \sigma_F/A_t$ as

$$A_t/A_B = \sigma_F/A_B R_B \tag{14a}$$

For the mid-range of Fig. 1, namely for $R_B \approx 1.5\text{x}10^{-4}\Omega$ at $A_B = 7.7\text{x}10^{-5}\text{m}^2$ (i.e. at $p_B \approx 2000\text{N/m}^2$) this renders

$$A_t/A_B \approx 5\text{x}10^{-5} = K^2 A_b/A_B \tag{14b}$$

Correspondingly, $\bar{p}$, the average pressure on the load bearing contact area A_b, is found as

$$\bar{p} = p_B(A_B/A_b) = p_B K^2(A_B/A_t) \approx K^2 4\text{x}10^7\ \text{N/m}^2 \tag{15}$$

Since the $p_B^{-2/3}$ dependence of the brush resistance has confirmed the hypothesis that the a-spots are elastically loaded, the value of $\bar{p}$ can at most be H/2 where H is the hardness[9], introduced in eq. 1 above as equal to about $6\text{x}10^8\text{N/m}^2$. Correspondingly, the result of eq. 15 limits K^2

to below 8, and more realistically to about 5, say. Namely, $R_B p^{2/3}$ is substantially constant up to loads four times higher as seen in Table II. Correspondingly

$$K \leq 2.5 \tag{16}$$

Next, the radius of the load bearing contact spots can be found by the use of eqs. 7, 8 and 14b as

$$r_b = d[A_b/A_B 4\alpha f]^{-\frac{1}{2}} \approx$$
$$1.3\text{x}10^{-7}/K\ [\text{m}] = 1300\ \text{Å}/K \tag{17a}$$

and

$$r_t \approx 1300\ \text{Å} \tag{17b}$$

The depth of the impression, h, by which the average contact spot is elastically depressed is found from Holm's relationship[9]

$$h/r_c = \tfrac{1}{2}(r_b/r_c)^2 \tag{18a}$$

which renders with egs. 13 and 17

$$h = \tfrac{1}{2}r_b^2/r_c = \frac{K}{2}\frac{(1.3\text{x}10^{-7})^2}{4.5\text{x}10^{-5}}\ [\text{m}] \approx 2K\text{Å} \tag{18b}$$

In order to assign a value to K, it is finally necessary to evaluate the critical radius, r_t, at which the gap between the two surfaces about the periphery of the a-spot is still small enough to permit electron tunneling at substantially the average tunnel resistance $\sigma_F = 5\text{x}10^{-13}\Omega\text{m}^2$. Presumably this is not far from s = 5 Å. As shown by Holm[10] the gap width is related to r_t, r_b and r_c as

$$s = (r_t^2 - r_b^2)/2r_c \tag{19}$$

Assuming, then, $1 < K < 2.5$, with r_t = 1300 Å (eq. 17b) it is

$$2.8\mu\text{m} < r_c < 45\mu\text{m} \tag{13b}$$

and

$$520\ \text{Å} < r_b < 1300\ \text{Å} \tag{17c}$$

The gap width is found at s = 5 Å when $K \approx 1.6_3$.

In summary, then, the numerical evaluation of the measurements indicates that the radius of curvature controlling the contact area was $r_c \approx 11\ \mu\text{m}$ which at the brush load of about ½ oz ≈ 0.15 N and α=3 a-spots per fibre gave rise to a-spots whose load bearing radius was $r_b \approx 812$ Å. Furthermore, the depth of penetration per a-spot into the fiber surface was h ≈ 3.2Å. Due to the very shallow impression, in turn due to the low force per a-spot, the radius within which effective tunneling could take place was 1.6_3 times larger than the radius of the load bearing part of the contact spot, namely $r_t \approx 1300$ Å, assuming that the average tunnel resistance was $\sigma_F = 5\text{x}10^{-13}\Omega\text{m}^2$ and that effective electron tunneling can take place within gap widths of ~5Å. This gap width equals, more or less, the thickness of the surface film separating the two sides of the metallic contact, and the assumed tunnel resistance is that of the surface films on clean gold in oxygen-free atmospheres.

Stationary Versus Dynamic Brush Resistance

The comparatively involved method that was used to arrive at the above values for the discussed parameters was chosen to keep ambiguities at a minimum. This should not obscure the fact that, physically, the surface roughness, the film thickness, the film resistance, and the number of a-spots per fiber, are well-defined quantities, even though we do not know their values with certainty. In the case of static contacts, the best known of these, even in the absence of any sophisticated theory of measurements, is the number of a-spots per fiber, i.e. the parameter α, provided that the packing fraction is low enough so that the overwhelming majority of the fibers contact the rotor. Namely, three points define a plane, and given that the a-spots are very much smaller than the fiber cross section, and given that the fibers are very slender and thus flexible, it would be difficult to argue for any number of a-spots different from three on stationary surfaces.

Conditions are different in relative motion when the asperities move past the individual fibers too fast to permit the slight flexing motions, superimposed on the overall bending of the fibers, which are required if the fiber ends shall always align themselves with the three most prominent asperities on the opposing surface. Correspondingly, beginning with very slow motions, the number of a-spots per fiber should rapidly decrease with speed, down to unity. Beyond this point, no small-scale flexing motions in response to the fluctuating force distribution at the fiber ends is fast enough to align them with the opposing asperities, and the fibers bend only in proportion to the total force acting on their ends. This should remain true until at very high speeds the jerky, almost Brownian fluctuations of the forces on the fiber ends imparts sufficient kinetic energy to them, to fling them off the rotor intermittently.

A simple argument shows that this effect, when operating in full strength, will decrease the momentary population of fibers in contact with the slip ring to moderately less than one half, say down to

perhaps one quarter, but hardly much lower. Namely, if the excited oscillatory bending motions of the fibers (slower than their fundamental resonance frequency or a multiple thereof) are assumed to be sinosoidal, the fiber ends would be stopped at the rotor surface through one half of each cycle and swing free through the other half. In fact the motion is anharmonic and the residence time of the fiber ends on the rotor would be somewhat below one half for that reason.

In general one may write for α^*, the number of a-spots per fiber when the brush is in relative motion, as compared to the same number, namely $\alpha \approx 3$, at rest

$$\alpha^* = Q\alpha = 3Q \qquad (20)$$

In accordance with the preceding arguments, we expect $\alpha^* = 1$ for a wide range of speeds, beginning with rather low velocities, provided that the packing density is low enough to permit individual fiber motion in response to the forces acting on their ends. At much higher speeds (in a range which is not yet known to us since it may well be above 35 m/sec, the limit of the measurements to date) α^* is expected to decrease down to perhaps 0.3 or so. In that range of Q values, i.e. below $Q = 1/3$, the fraction of fibers which at any one moment is in contact with the rotor is numerically equal to 3Q.

In all ranges of Q, the load per contact spot, P_b of eq. 5, is increased to

$$P_b^* = P_b/Q \qquad (21a)$$

and the radius of the load-bearing contact spots is increased to

$$r_b^* = r_b/Q^{1/3} \qquad (21b)$$

in accordance with eq. 5, using the * superscript to indicate the running condition of the brush.

Since the brush resistance increases with decreasing number of a-spots the preceding considerations predict a steep increase of brush resistance with increasing relative speed between brush and rotor, beginning from rest, which soon should saturate at a brush resistance which corresponds to one a-spot per fiber. This plateau should extend to some much higher speed beyond which the brush resistivity should increase again, eventually to correspond to, say, one third of an a-spot per fiber. At low brush pressure, this effect may be somewhat obscured by aerodynamic lift. The effect has the discussed, quite distinctly different physical cause, however, and it would operate in a vacuum just as well as under atmospheric pressure.

In order to assess the magnitude of the effect of changing a-spot numbers, i.e. of the parameter Q, with velocity, the first step must be to correct for aerodynamic lift. For the case of the brushes with 20 to 22 micron diameter fibers, Fig. 6 indicates that the brush resistance without aerodynamic lift would be lower by a factor of ~1.3 at 5 oz/in^2 ≈ 2000 N/m^2 and 13 m/sec velocity than the measured value of $4.45 \times 10^{-4}\ \Omega$ (see Table II). Correspondingly, $R_B^* \approx (4.45 \times 10^{-4}\Omega)/1.3 \approx 3.4 \times 10^{-4}\Omega$.

Taking the example of the 20 to 22 μm brushes, for which the pertinent parameters for the stationary case have been computed above, we may readily evaluate the relative increase of brush resistance due to changing value of a-spot numbers per fiber as follows: If s_o designates the maximum gap width for effective tunneling (previously assumed to be $s_o = 5$ Å), one finds for r_t^*, the new radius of the current carrying spots when the brushes are in relative motion,

$$r_t^* = K^* r_b^* = \sqrt{2 r_c s_o + r_b^{*2}} \qquad (22)$$

according to eq. 19, while from eq. 11b for the case of same brush pressure and current density

$$R_B^*/R_B = (K/K^*)^2 (\alpha/\alpha^*)^{1/3} = (K/K^*)^2/Q^{1/3} \qquad (23)$$

Using the same values as computed before, namely r_b, = 812 Å and r_c = 11 μm, K = 1.63 and s_o = 5 Å, yields the dependence of R_B^*/R_B shown in Fig. 9. The value of $R_B^* = 3.4 \times 10^{-4}\ \Omega$m for the brush when running, after correcting for aerodynamic lift, in relation to the static contact resistance at same pressure of $R_B = 1.6 \times 10^{-4}\Omega$ (see Fig. 1) for $R_B^*/R_B = 2.1$ is seen to correspond to Q = 0.97.

The same calculation may be made for the 100 μm brush. For it, Fig. 7 suggests a value of R_B^* corrected for aerodynamic lift of $R_B^* \approx 8.5 \times 10^{-4}\Omega$ while from Fig. 1 one finds $R_b \approx 3.5 \times 10^{-4}\Omega$ for $R_B^*/R_B = 2.3$. To the extent that Fig. 9 may be used also in this case, this ratio again suggests a value of α^* near unity.

It would seem, then, that the observed increase of brush resistance when running as compared to the stationary contact resistance is fully explained by the reduction in the number of a-spots as discussed. This hypothesis is in fine accord with the observed independence of brush resistance from rotor velocity as one of its most attractive features. Clearly, it is somewhat surprising that there should

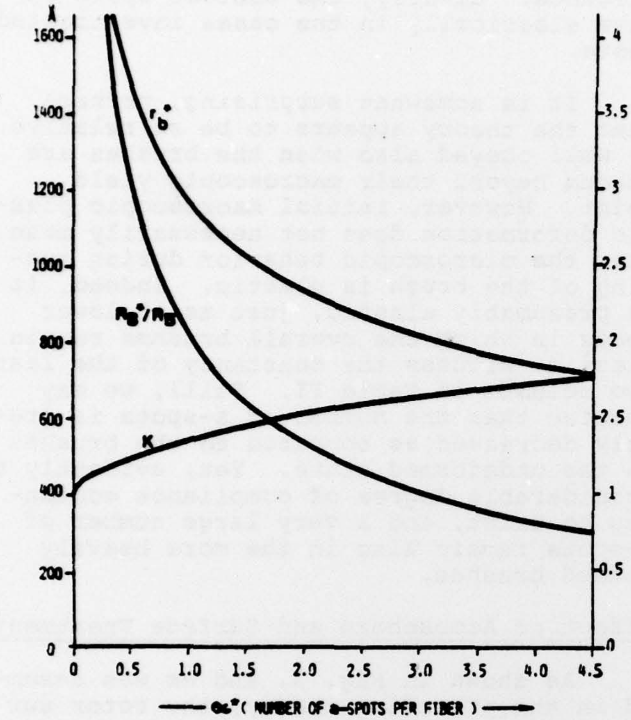

Figure 9: Dependence of brush resistance on number of a-spots per fiber. The numerical values pertain specifically to the 20 to 22 μm brushes of Tables I and II and the data depicted in Figs. 1, 3 and 6, at a brush pressure of about 2000 N/m^2. However, qualitatively the curves are characteristic for all lightly loaded fiber brushes of the discussed type. It is assumed that in the stationary case, the number of a-spots per fiber is $\alpha = 3$, while when the brushes are run it is $\alpha^* = 1$. The radius of the load bearing contact spots is r_b^*. The radius of the current carrying areas, r_t, is larger than r_b by the factor K on account of tunneling at the periphery of the a-spots.

be no dependence on speed between about 5 m/sec and 35 m/sec even while there is such an obvious increase between the moving and the stationary case. Yet, this is what is observed, and this is what the discussed considerations on the number of a-spots per fiber predict.

One other observation is in support of the hypothesis being discussed. Namely, when brushes, after running on a rotor, are removed from the apparatus and then reinserted for further testing, their resistance is almost always considerably higher than before. It is then generally necessary to increase the brush pressure to again obtain comparably good performance. Case #1 of Table II is an example. Considering the effect of changing a-spot number, it appears that misalignment is the cause, on account of which not all of the brush surface touches the rotor, thus reducing the number of a-spots. The phenomenon is hence easily understood on the basis of Fig. 9.

Brush Resistance as a Function of Fiber Diameter

A question which still must be answered concerns the relative resistances of the brushes with 20 or 22 micron diameter fibers as compared to brushes with 100 micron fibers. Namely, brush resistance was found to be proportional to $(d^2/\alpha f)^{1/3}/K^2$, but the 100 micron brushes, whose K value should be lower than of the 20 micron brushes, have a resistance that seems too low by a factor of at least 1.4, even disregarding the effect of K. Moreover, this cannot be considered to be some erratic aberration since we saw already that in regard to stationary contact resistance compared to contact resistance in relative motion, the 100 micron brushes perform according to theory.

It is suggested that the reason for this apparent discrepancy may be sought in an approximation made in eq. 5: What had been designated with the symbol r_c is in fact given by the radii of curvature of the two surfaces, say, r_{Au} and r_{Cu}, as

$$r_c^{-1} = r_{Au}^{-1} + r_{Cu}^{-1} \qquad (24a)$$

In the preceding considerations, the radius of curvature of the fiber ends was implicitly assumed to be infinite, while the surface roughness of the copper was tentatively assumed to control the value of r_c. However, the fiber ends could at the most have the same effect as a sphere indenter of same diameter, or a little larger on account of little "pads" which form on them through a process not yet understood (Fig. 10).

In this connection it may not be at all accidental that the value of r_c was found to be so nearly equal to the fiber radius for the 20 to 22 μm brushes, namely $r_c = 11$ microns in the preceding evaluation of parameters. It would thus seem that the surface roughness of the copper corresponds to a much larger radius of curvature than 11 microns and that, essentially, the value of r_c is determined by the fiber radius. Let us then assume that this is so and $r_{Au} \approx d/2$. The value of $r_c = 11$ microns would then suggest that $r_{Cu} \approx 100$ μm, in the stationary as well as dynamic tests. Note that Fig. 2

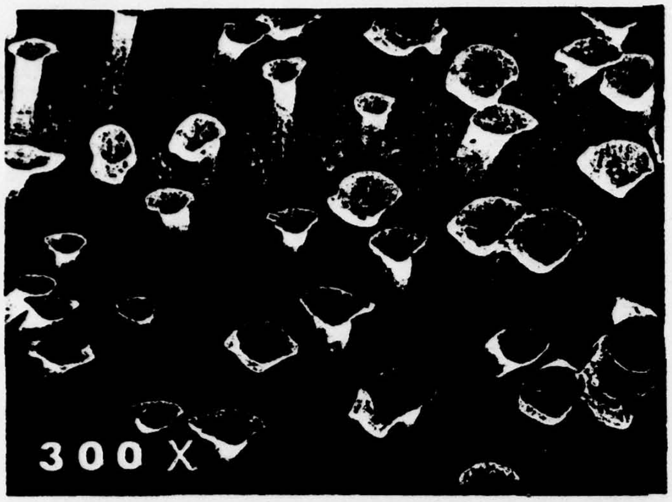

Figure 10: Scanning electron micrograph of the working surface of a silver-fiber/copper-matrix brush after use. The "pads" at the ends of the fibers are a common feature, but the mechanism for their formation is not as yet known.

supports the contention that r_c is not changed due to running of fiber brushes on the rotor.

For clarity, the values referring to the 100 µm fiber brush may be indicated with dashed symbols. The value of the radius of curvature, r_c' for 100 µm fibers is now found as

$$1/r_c' \approx 1/100\mu m + 1/100\mu m \qquad (24b)$$

i.e. $r_c' \approx 50$ µm, as contrasted with $r_c \approx 11$ µm for the case of the 20 micron brushes. Correspondingly,

$$R_B'/R_B = (K/K')^2 (r_c/r_c')^{2/3} (d'^2 f A_B / d^2 f' A_B')^{1/3} \qquad (24c)$$

on the basis of eq. 11. The numerical result is $R_B'/R_B \approx 1.8$. Here, experimentally A_B'/A_B was 0.83, namely $A_B = 0.77$ cm^2 and $A_B = 0.64$ cm, and $K' \approx 1.3$ as compared to $K = 1.6$ on account of the larger value of r_b compared to r_b (see eq. 22). The thus obtained agreement between predicted and observed resistance is within the limit of accuracy both for the stationary and running brushes. The curve computed with the resistance ratio of eq. 24c, i.e. incorporating all corrections discussed, is included in Fig. 1.

As was shown in the preceding discussions, the brush resistances obtained with the fiber brushes conform to the theory of contacts as developed above. Contrary to expectations, tunneling through the gap about the a-spots is significant and is effective in reducing the total brush resistance. Clearly, the contact spots behave elastically in the cases investigated above.

It is somewhat surprising, perhaps, that the theory appears to be so relatively well obeyed also when the brushes are loaded beyond their macroscopic yield point. However, initial macroscopic plastic deformation does not necessarily mean that the microscopic behavior during running of the brush is plastic. Indeed, it is presumably elastic, just as at lower loads in which the overall brushes remain elastic, witness the constancy of the last two columns in Table II. Still, we may surmise that the number of a-spots is greatly decreased as compared to the brushes in the undeformed state. Yet, evidently a considerable degree of compliance continues to exist, and a very large number of a-spots remain also in the more heavily loaded brushes.

Effect of Atmosphere and Surface Treatment

As shown in Fig. 2, and as was assumed in the preceding theory, the rotor surface does not exhibit significant changes when a brush is run on it. There is, however, some coloration, namely some darkening of the brush track when run in air, and some slight gold transfer in argon. Lacking any detailed experimental results in regard to the surface condition of the rotors after use, one may only speculate on the reasons for the beneficial effect of humidity, and the special surface treatment provided by the AMP Incorporated (Harrisburg, PA) laboratory. Holm's discussion of the effect of humidity[11] would lead one to suspect that the primary function of the higher moisture level is to displace additional oxygen rather than to increase the thickness of the adsorbed water film. It seems likely that, throughout, this remains at a thickness of about two monolayers in the load bearing area of a-spots, thus explaining the apparent constancy of σ_F. However, as humidity is increased the adsorbed water layer may well thicken to several layers outside of the load bearing area. This would have the effect of increasing the gap width through which tunneling is effective, and would correspondingly explain the decrease of brush resistance at 80% humidity as compared to a humidity mildly below 30%.

This hypothesis receives support from the observed increase of the coefficient of friction with humidity, namely from 0.31 at ≤ 30% humidity, to 0.40 at ≥ 80% humidity, within an error of perhaps 10%, as measured on the gold-carbon surface. The coefficient of friction is somewhat higher on copper (about 0.48 at the lower

humidity) which in the light of the present argument would imply that the adsorbed layer is thicker on copper than on the gold graphite surface. This is not a far-fetched assumption, of course, in view of the much greater proclivity of oxygen to absorb on copper than on gold. Regrettably, these considerations are still largely on the level of speculation for want of definitive experimental information. Certainly the surface films are rather complex, with sulfur apparently present under all circumstances as judged by auger studies.[12] As to its role, we know nothing.

More evident is the role played by oxygen, namely that its layers have a higher tunnel resistance, σ_F. One may assert with some degree of conviction, therefore, that the role of the argon atmosphere (or any other inert gas such as carbon dioxide, or nitrogen, or helium, all of which are effective, albeit not necessarily to the same degree) is that of excluding oxygen. This is helpful even without introducing water vapor. Still, by deliberately humidifying the cover gas, one permits the formation of an adsorbed water film of considerable stability, thus reducing the incidence of "wild" films of less predictable, and generally less favorable, properties. The presence of oxygen is always detrimental, it seems.

Brush Wear

The question of brush wear must still be investigated. The testing equipment permits monitoring distance changes between brushes and rotor during use so as to discover changes in brush position as small as about 10 microns. This is not totally adequate to the task in short-term testing, though. The difficulty is that there are at least two processes besides wear which show up as shortening of the fibers, including the formation of the "pads" (Fig. 10) and creep deformation so as to bend the fibers. Only careful long-term tests will reveal the probable lifetimes of the brushes under specific conditions of running. However, it appears that wear under favorable conditions of running is low.

As pointed out before, there are no easily discoverable changes on the rotor on account of use (Fig. 2) and the brush resistance is constant over a wide range of speed and current density. Furthermore, except for transient effects such as discussed in connection with case #1 of Table II, the measurements are reproducible within gratifyingly narrow limits. For example, a brush run first on copper and then on gold - carbon surfaces, shows the same brush resistance when retested on a copper rotor. Thus there is no evidence for permanent changes in brush performance as a function of running time.

The above observations together with the considerations on the adsorbed films strongly suggest that brush wear either is at an acceptably low level under the test conditions used, or can be lowered to such a level if need be. The theoretically derived depth of impression of the a-spot, h of eq. 18, being only a few to several Å, strongly supports this optimistic assessment of wear characteristics. Namely, such very small strains, even if completely due to plastic deformation and not to elastic deformation, are accommodated by only slight motions of a few dislocations. Correspondingly, fatigue and the associated mechanical damage must be virtually absent in both rotor and fibers. This is, of course, in accord with the apparent absence of damage or change in surface contour illustrated in Fig. 2.

CONCLUSIONS

The outstanding performance characteristics of the fiber brushes discussed in this paper are most encouraging. To be sure, gold fibers are expensive and it would be desirable to use another material. The reason for using gold in this study was a scientific one: It was desired to use a material which would yield the most reproducible possible results so as to be able to understand the brush behavior theoretically. As was shown, this objective has been achieved. From here on, the lessons learned may be applied in systems liable to be of great practical use in machinery even of modest to moderate cost.

The results given by Holm[2] regarding the contact resistances between metal pairs will be a very useful first guide as to choice of materials. It is in agreement with this expectation that platinum fiber brushes were found to have much higher resistances than silver and gold fiber brushes. Holm[13] indicates that this may be due to the formation of thin surface films of contact polymers.

On the basis of Holm's data, copper fibers should be very favorable, and experiments at the Westinghouse Laboratories using rather densely packed ~ 100 μm copper fibers have borne this out.[14]

The silver brushes tested by us had generally similar resistances as the gold brushes, but non-ohmic behavior at low current densities indicated the existence of a film thicker than in the case of gold brushes and subject to classical conduction in addition to, or instead of, tunneling. A set of niobium fiber brushes with very fine fibers (about 2 μm) tested

in air showed some surprisingly good results in initial tests, - surprising because Nb is pyrophoric. The brush resistance soon rose to very high levels, though, almost certainly due to oxidation layers.

The crucial points to be made at the conclusion of this paper are these: Firstly, the discussed type of fiber brushes exhibits the theoretically expected behavior to a gratifying degree of refinement. Evidently, the numerical values for r_b, σ_F and r_t could be in error by as much as a factor of two or even three, but the important point is that a set of values could be found which is wholly self-consistent. Thus, basically, the behavior of the brushes is understood.

Secondly, the theory suggests that this type of brush approaches the ideally best performance of solid brushes. Thirdly, there still exists much scope for improvements. Namely, the fraction of the geometrical contact area through which current is conducted amounts to only about 0.001%. By skillful surface treatments it should be possible to substantially increase this fraction at same loads.

One possibility to achieve this end will be the decrease of the effective modulus of rigidity at the rotor/brush interface. Most importantly, the brushes should be developed to the point that they can be used routinely with minimum special precautions. Even now the brushes when run in air are superior to monolithic brushes but it falls far short of their performance in moist argon.

The so far best performance under optimum conditions, was the transmission of current at 4000 $A/in^2 \approx 650\ A/cm^2$ at 35 m/sec, i.e. better than 70 mph, with a loss of only about 0.1 watt per ampere conducted. This result makes it probable that this new brush type will have wide future applications. The actual limits of performance of the brushes in terms of current density and speed have not yet been determined. By expanding experimental testing capabilities these should be known before long.

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Electrical brushes made of very fine metal fibers have been made and tested. The results are most promising. Additionally the surface films on silver graphite brushes have been investigated. These appear to consist of a thicker layer of lubrication material and a thinner layer which presumably is a very thin layer of oxide and/or water. The former layer is subject to build-up and destruction in the course of running the brushes A theory was made which is consistent with observations on fiber brushes